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HiMAT Flight Program: Test Results and Program Assessment Overview

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INTRODUCTION

Flight tests have been completed on the highly maneuverable aircraft technology (HiMAT) program at Dryden Flight Research Facility of NASA Ames Research Center (Ames-Dryden). A symposium was held at Ames-Dryden on May 22 to 24, 1984, to discuss the results of those tests (ref. 1). This paper presents a summary of the test results.

Two HiMAT vehicles were designed and built to demonstrate several advanced fighter technologies while taking advantage of the beneficial aspects of flight test with the use of a remotely piloted research vehicle (RPRV). The program was conducted jointly by NASA and the U.S. Air Force, with Rockwell International as the prime contractor. The major advanced technologies incorporated in the HiMAT RPRV were close-coupled canard planform, aeroelastic tailoring with composite structures, and relaxed static stability. A primary emphasis was placed on the validation of design tools with flight test results.

Another major emphasis was the integration of the various advanced technologies. Previous flight research programs have attempted to isolate the technology of interest from the other more conventional technologies. This program sought major benefits through the interactions among the advanced technologies, with the expectation of further benefits through synergistic effects. Such an objective provides a major challenge to the researcher who is trying to understand the contributions of the individual technologies.

A secondary objective of this program was to evaluate the RPRV technique as applied to a sophisticated vehicle for the first time. The overall program included conceptual design and its comparison with a hypothetical full-scale vehicle, design of the subscale version, fabrication of two test vehicles, and subsequent flight test. This paper discusses in detail the pertinent aspects of the RPRV approach and presents the major findings on its applicabilities to a HiMAT type vehicle.

NOMENCLATURE

BCS	backup control system
b	wingspan, m (ft)
C_L	airplane lift coefficient, lift/$\bar{q}S$

C_n	airplane yawing moment coefficient, yawing moment/qSb
C_{n_β}	directional stability derivative, $\partial C_n/\partial\beta$
C_p	pressure coefficient, $(p_e - p_\infty)/\bar{q}$
c	wing local chord length, m (ft)
FTMAP	flight test maneuver autopilot
HiMAT	highly maneuverable aircraft technology
j	$\sqrt{-1}$
LED	light-emitting diode
MAC	mean aerodynamic chord, m (ft)
NASTRAN	NASA structural analysis finite-element modeling program
P_s	specific excess power, m/sec (ft/sec)
p_e	local static pressure, kN/m^2 (lb/ft^2)
p_∞	freestream static pressure, kN/m^2 (lb/ft^2)
$\bar{q}$	dynamic pressure, $1/2\rho V^2$, kN/m^2 (lb/ft^2)
RPRV	remotely piloted research vehicle
S	wing reference area, m^2 (ft^2)
V	velocity, m/sec (ft/sec)
x	distance aft of leading edge of local chord, m (ft)
x/c	fraction of local chord length, m (ft)
y	spanwise distance, m (ft)
β	angle of sideslip, deg
ΔC_D	incremental drag coefficient, incremental drag/$\bar{q}$S
η	fraction of semispan, 2y/b
ρ	density, kg/m^3 ($slugs/ft^3$)

DESCRIPTION OF VEHICLE AND TEST APPROACH

The HiMAT vehicle, including overall dimensions, is illustrated in the three-view drawing of figure 1. It is a subscale version of a hypothetical full-scale manned vehicle. The vehicle is characterized by a swept wing with a close-coupled canard. Both wing and canard have a modified supercritical airfoil section designed to optimize the transonic maneuvering aerodynamics of the vehicle (ref. 2). The vehicle is launched from a B-52 aircraft and, through piloted control and augmentation from a ground-based facility, is flown for test purposes and landed horizontally on landing gear skids on the dry lakebed at Edwards Air Force Base (fig. 2). Closed-loop control makes use of uplink, downlink, and onboard telemetry. Signals from rate gyros, air data sensors, and accelerometers are transmitted to the ground through the telemetry system and are input to the ground-based computer that contains the vehicle control laws. An onboard computer system based on two microprocessors provides primary system interface and redundancy management, as well as backup control functions (fig. 3).

The backup control system (BCS) allows emergency operation, can recover the vehicle from unusual or extreme attitudes, provides well-controlled vehicle dynamics throughout the flight envelope, and is capable of landing the vehicle with minimal command inputs. Transfer to the BCS can be made manually either from the ground or the TF-104G chase aircraft, or automatically in the event of certain system failures or loss of uplink or downlink signal carrier. With the BCS, the operation of the vehicle is controlled by the onboard computer with limited discrete control inputs from the ground-based cockpit or the chase aircraft.

To achieve the research objectives, special instrumentation was installed. One of the most advanced was for measurement of wing and canard flight deflections. Targets consisting of light-emitting diodes (LEDs) were mounted on the upper surfaces of the wing and canard, and receivers were mounted in the fuselage (fig. 4). With this arrangement, targets are activated sequentially, and the infrared light produced by the targets is sensed by the light-sensitive diode array of the receiver. A digital word that is proportional to the point at which the target light impinges on the diode array represents the target deflection and is recorded on tape for later analysis. A detailed description of the deflection measurement system and its use on the HiMAT vehicle is presented in reference 3. Other instrumentation for flight test was more conventional. Pressure distributions were obtained on the right-hand wing and canard from a set of pressure trandućers mounted in the wing leading edge. A standard set of motion sensors was included for flight control, stability and control, parameter identifications, and buffet measurements.

An important feature was a newly developed flight test maneuver autopilot (FTMAP). The system (ref. 4 and fig. 5) had preprogrammed maneuvers, such as a constant Mach windup turn, that were implemented as an outer-loop command bypassing the pilot stick. These commands became the commands to the primary control laws that forced the vehicle to fly the desired maneuvers. Also shown in figure 5 are examples of key parameters before (manually flown) and after FTMAP was installed.

Note that the buildup of angle of attack and load factor is smooth when the FTMAP is used. The endplate accelerometers for the maneuver having FTMAP engaged display more precisely defined buildup of vibration, indicating a definite onset of buffet and, correspondingly, more reliability in the data.

FLIGHT PROGRAM OVERVIEW

The approach of the flight program was to build two test vehicles, one devoted principally to envelope expansion and the other to research data collection. The vehicles were designed to operate at negative static stability levels (ref. 5). However, the initial flight tests on vehicle 1 were ballasted with lead weight to give a more forward center of gravity and, in turn, a positive static stability level. After an improved aerodynamic model was obtained, based on flight-measured data, the ballast was reduced, thereby moving the center of gravity aft and relaxing the static stability level. Although the static stability level was reduced to approximately neutral, it was never reduced to the full negative stability design value. The center of gravity was not moved fully aft because it was believed that the most important program objectives could be adequately met at neutral stability levels. Moreover, the required verification and validation of a modified set of control law gains would have been achieved at the expense of other nigh priority research programs.

Figure 6 provides a summary of the stability levels flown, as compared with the predicted levels. Stability level, in percent mean aerodynamic chord (MAC), is the difference between the neutral point and the center-of-gravity position. (By convention, negative values indicate positive stability.) The ballasted stable center-of-gravity range was between -8 and -5 percent MAC. This would have given a predicted positive stability level range of -7 to -10 percent MAC at Mach 0.4. The neutral point measured in flight was approximately 2 percent MAC farther aft; hence, the measured stability level was between 9 and 12 percent MAC stable. The farthest aft center-of-gravity range flown was about -3 to -6 percent MAC, or a static stability level centered about neutral. The design center of gravity was 10 percent MAC aft. Therefore, if the flight tests had included that point, the static stability level would have been approximately 6 percent MAC negative.

The flight program began in mid-1979 (fig. 7). HiMAT vehicle 1 was used for envelope expansion and design point demonstrations, one at a transonic maneuver point and one for supersonic endurance demonstration (a total of 14 flights). Vehicle 2 began flight test in mid-1981 and was used to complete the research flight program (12 additional flights). The maneuver points for various altitudes and Mach numbers are shown in figure 8.

PERFORMANCE GOALS AND ACCOMPLISHMENTS

An important factor in providing some degree of realism in the design of the HiMAT vehicle was the inclusion of multiple design points. Two performance goals--one transonic for maneuverability and the other supersonic for endurance--were established. This multiple goal constraint forced design compromises that are typical in any operational airplane design, although not as extensive as those usually encountered. For example, operational airplanes have additional constraints such as the provision for hard points for carrying wing stores.

The most important goal was the transonic maneuverability target of 8 g sustained at Mach 0.9 and 7620 m (25,000 ft). Some interpretation was required, in that the vehicle was not flown at the 10 percent aft center-of-gravity design position. However, trends in sustained g level based on several more forward positions than the design center of gravity provide strong confidence that the performance goal could have been exceeded. In addition, the sustained g levels at the farthest aft center-of-gravity location flown (5 percent aft) agreed with the predicted values for that center of gravity (ref. 6).

For the supersonic endurance point, the goal was to sustain a 3-g turn for 3.5 min at Mach 1.4 and 12,190 m (40,000 ft). Because of practical flight test constraints, this maneuver was sustained for less than 3.5 min, with the projected duration determined from fuel flow data obtained during the maneuver. However, performance was much better than predicted, in that a 4-g turn was achieved while meeting Mach number, altitude, and projected endurance conditions.

RESULTS OF INDIVIDUAL DISCIPLINES

The flight test measurements from the HiMAT program make a valuable data base for comparison of the various applicable design and analysis tools. Comparisons have been made in the various disciplines, both relative to the original design computer codes and to some more recent codes that would be expected to provide better fidelity in the modeling. The principal findings in the disciplines of structures, aerodynamics, flight controls, and propulsion controls will be discussed individually as if each were an isolated discipline unaffected by the others.

Structures

The wing and canard are graphite-epoxy composite structures that were aeroelastically tailored to maximize the streamwise twist due to load (ref. 7). Hence, achievement of the desired streamwise twist angle (built-in twist plus twist due to load) at the maneuver design point would minimize the amount of washout at supersonic cruise. In deflection measurements made both during ground load tests (ref. 8) and in flight under various loads (ref. 9), the wing and canard twists were approximately 20 percent less than had been predicted.

Figure 9 presents a comparison of streamwise twist for both the wing and canard. Flight data are compared with ground test values and predicted results from the NASA structural analysis (NASTRAN) finite-element modeling program. For the RPRV, the flow was separated on the end plate and part of the outer wing panel and canard at the maneuver design point. The streamwise twist data shown for this separated-flow maneuvering condition is termed "actual" and represents the true twist due to load of the HiMAT RPRV at the maneuver design point. The NASTRAN predictions and ground test data were derived from predicted maneuver design loads without separated flow. To afford a meaningful comparison of structural deformation between predicted data and flight measurements, the flight data were linearly extrapolated to the maneuver design point using the flight data obtained prior to flow separation. These data are termed "linearly extrapolated" (fig. 9) and represent the streamwise twist that would have been measured at the maneuver design point if the flow had not separated. The canard reference plane for determining the canard twist was unreliable. Hence, the flight data were adjusted to match the ground test data at the 70-percent span points in order to provide a meaningful comparison of the streamwise twist of the wingtip station relative to the twist at the 70-percent span station.

A number of corrections to the NASTRAN model were made to account for the overpredictions in twist (ref. 10). The most probable cause for the overprediction was that the characterization of the composite materials was somewhat in error (ref. 11). The error was a direct result of the HiMAT design philosophy, that of minimizing the ground and laboratory test time in order to move quickly into flight and of accepting the higher risk involved. In this case, coupon testing of the matrix-dominated composite layup was not done until after the ground tests revealed the lower than predicted twists.

The degree of accuracy obtained in measuring loads on the nonstandard matrix-dominated composite layup of the wing and canard was unknown. Rather than attempt to develop a new measurement technique, the standard strain gage loads measurement technique was used, and it provided accurate loads measurements (ref. 12).

Aerodynamics

In HiMAT aerodynamics, it was clear that the aerodynamic configuration performed as well as or better than the original design predictions. Because of significant improvements in aerodynamic codes, the most current codes from two companies were used to predict the wing and canard pressure distributions. One was from Rockwell International, using a full-potential flow aerodynamic prediction program (Flow-28, ref. 13). The other was from Grumman Aerospace Corporation using the NASA-Grumman transonic wing-body code (ref. 14). Pressure distribution flight data were obtained and compared with these predictions. The flight data were of excellent quality and repeatability (refs. 4 and 15).

Figure 10 illustrates the repeatability of the pressure coefficient data taken from four flights at two span stations located on the outer wing panel. Data were collected both with and without the use of the FTMAP. Overall, the improved codes gave excellent agreement with the flight data. The original design codes gave reasonable results although flow separation was not predicted (nor should it have been because the codes were for analyzing inviscid flow).

Static stability levels in the subsonic regime were more stable than predicted longitudinally but less stable than predicted directionally (ref. 16). The predicted directional stability levels were unusually low. Hence, further reduction in stability led to handling qualities problems and necessitated the redesign of the lateral-directional flight control system. Significant differences in trim surface position, both transonically and supersonically, were attributed to poor predictions of pitching moment at zero lift, a difficult parameter to predict.

The significant increase in the size of the buffet-free envelope over that of present-day fighter aircraft was another indication of outstanding HiMAT aerodynamic performance. However, some difficulties were encountered in measuring the buffet onset point because of deficiencies in the accelerometer mountings. The FTMAP compensated for the poorer quality of the accelerometer signals by providing a very smooth buildup of angle of attack while entering buffeting during the windup turn test maneuver.

Flight Controls

The major contributions of the HiMAT program in the flight controls discipline are in the relaxed static stability area. Although the vehicle configuration that was ultimately flown was only slightly negative in stability, much simulation and checkout work was accomplished at the design center of gravity having significant instability levels. Table 1 lists the open-loop roots for two analytical models used in the design (ref. 17). The original model was based on predicted longitudinal data prior to the first flight. The final model is based on an aerodynamic model corrected to reflect flight determined derivatives.

The time to double amplitude, a measure of the dynamic instability, is significant (table 1). With regard to the approach condition, where control effectiveness is down and high gains are needed to stabilize the vehicle, the time to double amplitude is 0.45 sec. This is approximately the same as the predicted value (0.43 sec) for the X-29A aircraft. The negative stability margins in terms of percent mean aerodynamic chord are considerably different--10 percent for HiMAT as compared with 35 percent for X-29A. However, the dynamic instability levels are the same. The HiMAT was never flown at this instability level. Nevertheless, extensive ground testing was performed with hardware-in-the-loop simulation and would have provided an adequate longitudinal flight control system for actual flight. Before the center of gravity could be moved 10 percent aft, a problem area in the lateral directional axes would need to be reworked.

The system technology for the microprocessor-based computer presented a challenge. A multirate system involving four different sample rates, plus an asynchronous latch-up with the ground-based facility, was necessary for closed-loop primary control (ref. 18). An early model microprocessor (Intel 8080A) was used in a dual-microprocessor configuration, one of the first applications of microprocessors in aircraft flight control. Table 2 lists the various functions and the corresponding computational rates implemented in the two microprocessors.

Other important factors in system design included the failure conditions and recovery ground rules. The requirement that no single failure should result in loss of the vehicle led to increased design complexity and extensive failure modes and effects testing. Nevertheless, the flight program was successful, with no vehicles lost. However, one failure situation forced a permanent transfer to the BCS. A procedural problem associated with modified software for the flight (indirectly caused by inadequate testing of the newly released software) resulted in the inability to lower the landing gear. The landing was made with the gear up using the backup semi-autonomous automatic landing system. Even with these failure conditions, the landing was excellent, with almost no vehicle damage. Figure 11 shows how well the vehicle tracked the scheduled descent and flair profile.

Propulsion Controls

In the propulsion controls area, the hydromechanical engine control system on the J85-21 engine was replaced with a digital control system. It performed the necessary functions well, with the flexibility of the digital system affording easy adaptability to the various mission programmatic requirements. The digital system had multimode capabilities, with a high-stability mode and a combat mode in addition to the normal stability. Comparisons between flight-measured performance and predictions were generally quite good (ref. 19). Figure 12 illustrates the performance of the digital propulsion control system for the high-stability mode.

INTERDISCIPLINARY RESULTS

Previous flight research programs conducted at Ames-Dryden have focused primarily on a single new technology rather than considering several new technologies together. For example, the F-8 supercritical wing program emphasized use of advanced technology only in wing aerodynamics, although aeroelastic tailoring was also required to assure correct twist at cruise. The control systems were uncoupled and of very conservative and noninteracting design. On the other hand, the HiMAT program was intentionally highly coupled from the onset. There are contributions to the total performance that result from the interactions between disciplines and can be completely understood only when viewed from this broader perspective.

One expectation from the HiMAT program was to obtain synergistic benefits through the integration of multidisciplinary technologies. This expectation was based primarily on the large reductions in vehicle weight projected during the full-scale vehicle trade studies. However, to validate fully the synergistic benefits, two major efforts are required. First, it is necessary to validate design tools based on good agreement with the flight results from the vehicle with a complete set of technologies. Second, these tools must be exercised to obtain several alternate designs, each with a different set of technologies removed--thereby exposing the contribution of the individual technologies. These alternate designs must be done in considerable detail, or the results may yield misleading conclusions. Alternate designs at this level of detail were beyond the scope of this program; hence, a full validation of the synergistic benefits was not obtained.

The fact that the total vehicle met or exceeded its design goals does not necessarily validate all the individual design tools used. In the case of the HiMAT vehicle, several of the contributing technologies were achieving less than the design predictions. Others were performing better than predicted, thereby allowing the total vehicle to perform adequately. Several modeling areas need further work before the total design process is validated. An argument could be made that, for the HiMAT, the foremost need is for accurate prediction of zero-lift pitching moment at supersonic speeds.

In meeting the overall design goals, a key technology that depends heavily on interactions between the disciplines is aeroelastic tailoring through nonstandard composite layups. An attempt was made to determine the importance of the non-standard composite aeroelastic tailoring on the overall maneuvering performance (ref. 9). Figure 13 shows the relationships of several performance measures based on various wingtip twist angles. The curves are the contractor's originally predicted performance penalties at various lift coefficients for failing to obtain the desired twist of -9.5 deg. The original NASTRAN model predictions indicate that -9 deg should have been obtained. Projecting the linearly extrapolated flight data to the maneuver design point shows that -8 deg of twist could be obtained if the flow over the wingtip had not separated. At the point where the specific excess power is equal to zero ($P_s = 0$), the flight-measured wingtip twist is -7 deg. If conventional composites rather than nonstandard matrix-dominated ply layup were used, the predicted twist angle would have been between -6 and -7 deg. Based on original predictions for a lift coefficient of unity ($C_L = 1.0$), the penalty in P_s for not achieving the desired twist is approximately -5 m/sec (-16 ft/sec). Figure 14 provides a relationship between P_s and normal acceleration at a flight condition near the maneuver design condition, taken from flight data. The performance penalty is very small, on the order of 0.05 g. From this analysis, the inclusion of nonstandard composite ply layup to obtain the maximum benefit from the interacting disciplines appears to have a negligible effect on overall performance.

Because of some inaccuracies in modeling, interactions between disciplines became significant to the overall program. For example, flight controls are affected by inaccuracies in modeling certain aerodynamic stability and control parameters. The directional stability C_{n_β} was much smaller than modeled. Even with sensitivity analysis as part of the control system design, the system was not sufficiently robust to handle the actual C_{n_β} encountered. The net result was that the flight control laws required redesign to provide adequate lateral-directional handling qualities. In this case, the disciplines were closely coupled and could be considered as one discipline; inaccuracies in one strongly affected the performance of the other.

As expected, disciplines that were very loosely coupled did not display sensitivities within one discipline to the modeling errors in the other. For example, the propulsion system had very little coupling with the flight control system. Consequently, a relatively unsophisticated engine model was adequate. The errors between predictions and flight caused no discernible effects on the flight control system.

REMOTELY PILOTED RESEARCH VEHICLE ASSESSMENT

The RPRV assessment begins with an evaluation of the quantity and quality of research data, as compared with that from manned aircraft programs at Ames-Dryden. Some of the implications of using a subscale vehicle are appraised, followed by a consideration of the unmanned aspects. As the vehicle turned out to be quite complex, some of the reasons and ramifications are discussed and costs are presented.

Research Data Assessment

The research data were assessed from both a quantitative and qualitative standpoint. Table 3 lists the various technologies or research areas and a subjective judgment on the quantity, quality, and overall assessment of each. These assessments were made by the individual researchers as they related to the researchers' previous experience in manned full-scale aircraft programs. Quantity was judged relative to the research experiment objectives, which in many cases were reduced in scope from typical manned aircraft programs. For example, checking out the entire flight envelope of the HiMAT vehicle was not a program objective, although it is on most full-scale research airplane programs. Quality is primarily a function of the accuracy of the instrumentation pertinent to the research experiment, as well as the ability to achieve the necessary maneuver and conditions within desired tolerances. The overall assessments were obtained by combining subjectively the two previous assessments.

Subscale Considerations

Before the acceptable range of scale factors was determined, similitude studies were conducted by the three competing preliminary design contractors. These contractors were in general agreement that a scale factor of 0.4 or larger would provide adequate similitude to a full-scale fighter aircraft counterpart. The primary objective was in validating the design tools, although there may have been significant differences in some design details. One example in which the differences were large was in the wing construction. A full-scale HiMAT wing would probably be constructed using a multicell box. The subscale HiMAT vehicle, on the other hand, was constructed using full-depth aluminum honeycomb with bonded skins. Even with that difference, however, the design tools for a full-scale vehicle could be adequately validated with the subscale HiMAT.

The other implication of a subscale HiMAT vehicle is the limited volume for both instrumentation and fuel. The volume decreases according to the cube of the scale factor (fig. 15). Thus, the volume of the subscale vehicle is drastically reduced to less than one-tenth of the full-scale airplane. This reduced volume has a major impact on flight time. For the subscale HiMAT with a scale factor of 0.44, more than twice as many flights would have been required for the same amount of data in the full-scale counterpart. This implied requirement for a large number of flights was reduced by carefully planning each flight on the simulator and maximizing the usable flight data time of each flight. The FTMAP also helped to reduce the necessary flight time.

Comparison of Manned and Unmanned Flight

The HiMAT vehicle was assessed from the standpoint of its being unmanned. A higher level of risk in some areas was considered to be acceptable when compared with a manned vehicle. For example, flutter model and materials characterization tests were not performed; thus, more reliance was placed on analytical predictions. Some types of risk persisted throughout the program because th vehicle was unmanned. One risk that accompanied each landing was that of landing manually with limited visual cues and no motion cues.

It is well-recognized that data on flying qualities of a subscale unmanned vehicle would be of limited value in extrapolating to a full-scale manned airplane. The subscale aspects of the vehicle restricted further the usefulness of the flying qualities data. Flying qualities and handling qualities information was useful, however, when gathered relative to RPRV landings as no extrapolation was needed.

A test program that employs unmanned rather than manned vehicles has less support from the pilot community in the advocacy of follow-on programs. However, the degree to which this attitude affects new programs is difficult to assess. Nevertheless, it was undoubtedly a factor in the relatively early termination of this flight program, when compared with the durations of most manned flight programs.

The cost of manned programs as compared with unmanned programs is difficult to evaluate. A number of items must be addressed in a manned vehicle that were never factors in the unmanned HiMAT. However, they were balanced out to some extent by such additional items as the alternate command station in the TF-104G chase aircraft.

Systems Complexity

Systems complexity was a prominent characteristic of the HiMAT RPRV. This RPRV was the first such vehicle flown at Ames-Dryden that provided for a fail-safe horizontal landing. Other RPRVs have either used midair recovery for a safe return to base or have relied on a parachute as a backup for the primary system. The fail-safe horizontal landing capability substantially increased the system complexity. This complexity was most apparent in the various simulations, with the most extensive simulation requiring 10 interconnected computers working simultaneously and correctly with the vehicle itself in the loop.

At the time, the HiMAT vehicle was the most complex vehicle ever flown at Ames-Dryden. However, such vehicle complexity is the trend in future aircraft design. From experience gained in checking out these complex systems, the importance of a final ground check of all systems working together in a closed loop is clearly demonstrated and is a key to a high-integrity system.

The program duration was typical for manned vehicle programs, that is, about 10 years including 3 years in the flight phase. Because of their relative simplicity, other RPRV programs flown at Ames-Dryden such as the spin research vehicle and the 3/8-scale F-15--both of which were based on an unpowered relatively simple aircraft--were of relatively short duration (say, 2 to 3 years).

Program Costs

The cost of the HiMAT program will be viewed first from the standpoint of projected cost compared with vehicle scale size and then from the standpoint of an estimate of actual costs compared with these projections. Figure 16 shows some cost estimates as a function of vehicle weight that were made early in the program. The curves were generated using some standard cost-estimating programs based primarily on vehicle weight and previous one-of-a-kind experimental aircraft. The costs are presented in 1973 millions of dollars. The solid-line curve in figure 16 is for two vehicles; the dashed-line curve is for the first vehicle only. Estimates include that for the incremental cost of supporting a man on board, as well as that for a minimum weight of 3500 kg (8000 lb) for a manned vehicle.

In retrospect, the percentage of cost attributed to the control system was underestimated. A control system dominated by software should have very little variation in cost with vehicle weight. Therefore, the overall curve should be closer to horizontal, but at a higher overall cost than that shown.

An approximate cost for the two vehicles in the flight-ready state was determined. Table 4 provides these estimates, rounded to the nearest million dollars. For the detailed design and fabrication contract, which culminated in the delivery of two vehicles, the cost before rounding off was 17.3 million (1973) dollars. The other numbers are approximate and include contractor support, government salaries, and government overhead. Both current-year dollars and equivalent dollars for fiscal year 1984 are shown. The two vehicles delivered under the contract were not complete. Therefore, the preparation for flight represents the additional system modifications and checkout necessary to become ready for the first flight. More expense is associated with vehicle 1, although it was more fully complete when delivered than was vehicle 2. Vehicle 2 checkout required much less time than vehicle 1 because most of the problems had been corrected during vehicle checkout.

A comparison of the actual cost with the original estimated cost is shown in figure 17. The HiMAT vehicle cost is placed on the same curve shown in figure 16 but is given in 1984 dollars. The cost of the HiMAT vehicle was somewhat higher than the study predicted but is reasonable when the costs of a control system dominated by complex software are taken into account.

Although precise numbers are not available, typical full-scale research airplanes, such as the X-29A, with vehicle weights of about 6000 kg (13,000 lb) have costs of over 100 million dollars. Thus, from the rough estimates, the projected costs from figure 17 are not unusually high.

CONCLUSIONS

The flight program for the highly maneuverable aircraft technology (HiMAT) vehicle provided a data base for validation of design tools appropriate to highly maneuverable aircraft. The program also demonstrated an advanced multidisplinary configuration that met or exceeded the performance design goals. However, not all design goals in the individual technologies were met. For example, the aeroelastic tailoring design goal was not achieved. Nevertheless, because other technologies more than met their goals, the overall performance goal was met. In carrying out this advanced technology program, the following conclusions were reached:

- Significant performance gains were possible through integration of the multidisciplinary advanced technologies.

- The data quality was excellent in the primary research areas, even with the constraints of minimum volume on instrumentation and flight time.

- Current design tools have been validated by the flight results, and newer design tools will continue to be validated as more comparisons are made with the flight-determined data base.

- The remotely piloted research vehicle (RPRV) technique, as adopted in this program, resulted in a more complex and costly vehicle than expected. However, the costs were considered reasonable when compared with alternative ways of obtaining comparable results.

Other outputs from the flight program were the identification of several areas requiring further research. The most notable of these was the need for better modeling of transonic and supersonic trim surface deflections, with particular attention to the zero-lift pitching moment that plays the dominant role in determining these deflections. More research is also needed in the relaxed static stability area, with identification of the factors that ultimately limit the ability of the systems to provide the necessary augmentation.

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TABLE 1.- HiMAT LONGITUDINAL DYNAMICS (OPEN LOOP)

Flight condition	Original model[a]		Final model[a]	
	Eigenvalues	Time to double amplitude, sec	Eigenvalues	Time to double amplitude, sec
Mach = 0.9, altitude = 7620 m (25,000 ft)	-7.30 -0.23 -0.71 3.90	0.18	-1.5 ±5.4j -0.06 0.04	19
Mach = 0.4, altitude = 762 m (2500 ft)	-0.014 ±0.12j -6.2 2.5	0.27	-0.09 ±0.08j -5.0 1.5	0.45

[a]Ten percent aft center of gravity.

TABLE 2.- HiMAT AIRBORNE COMPUTER SYSTEM FUNCTIONS

Function	Computational rate, Hz
Primary computer (microprocessor)	
Aircraft control by means of primary control system[a]	53.3
Uplink processing	106.6
Downlink processing	220, 55
Failure management	55, 53.3, 50, 25, 10, 1
Backup propulsion control[b]	50
Interrupt processing	2420, 106.6, 100, 75
Miscellaneous functions	50, 25, 10
Backup computer (microprocessor)	
Aircraft control by means of backup control system[c]	100, 50, 10
Uplink processing (discrete)	50
Failure management	50, 10, 1
Integrated propulsion control	33.3
Interrupt processing	106.6, 100
Miscellaneous functions	50, 10

[a]Primary mode only.
[b]Only if backup computer failed.
[c]Backup mode only.

TABLE 3.- RESEARCH DATA ASSESSMENT

Technology area	Data quantity	Data quality	Overall assessment
Structures			
Loads on composite structure	Marginal	Excellent	Very good
Deflections and twist	Marginal	Excellent	Very good
Aerodynamics			
Pressure distributions	Adequate	Excellent	Excellent
Specific excess power	Marginal	Good	Fair
Buffet	Adequate	Fair	Fair
Controls			
Stability and control	Adequate	Good	Good
Relaxed static stability	Marginal	Good	Fair
Digital fly-by-wire	Adequate	Excellent	Excellent
Propulsion controls	Marginal	Good	Good

TABLE 4.- APPROXIMATE COST FOR TWO FLIGHT-READY VEHICLES

Program stage	Cost in millions of dollars	
	Current-year dollars	1984 dollars
Design and fabrication contract	17	30
Preparation for flight		
Vehicle 1	4	7
Vehicle 2	2	3
Total	23	40

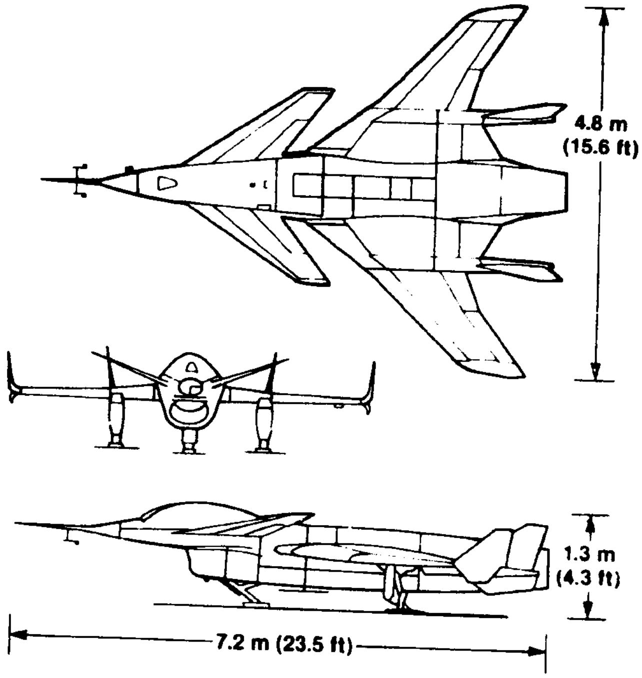


Figure 1. HiMAT remotely piloted research vehicle.

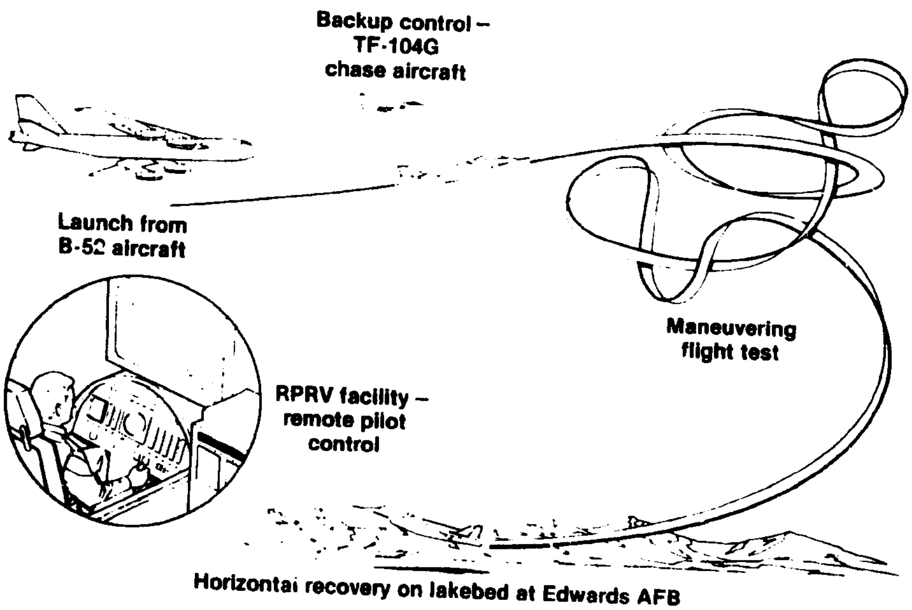


Figure 2. HiMAT operational concept.

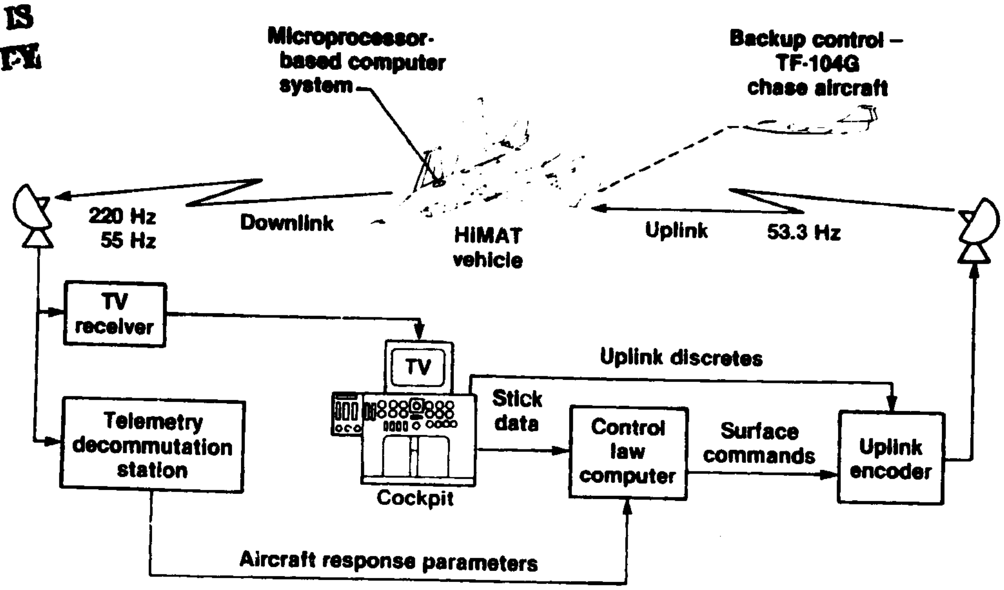


Figure 3. Control system for HiMAT remotely piloted research vehicle.

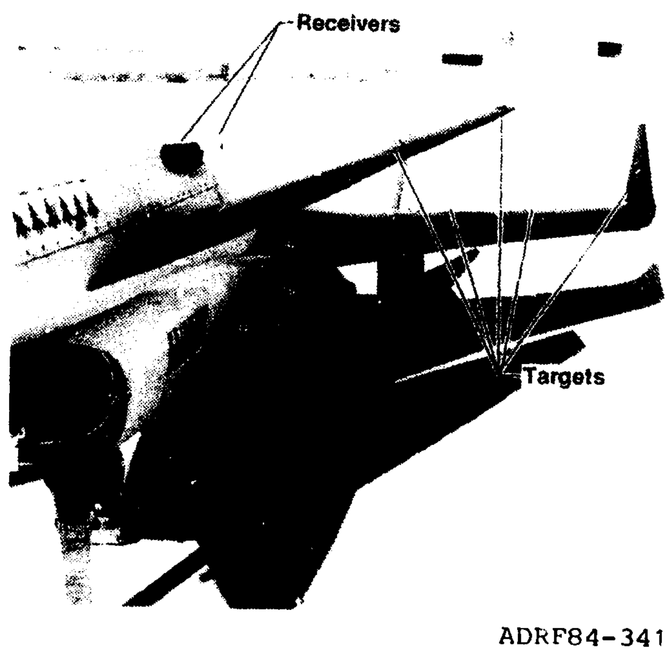


Figure 4. HiMAT flight deflection measurement system.

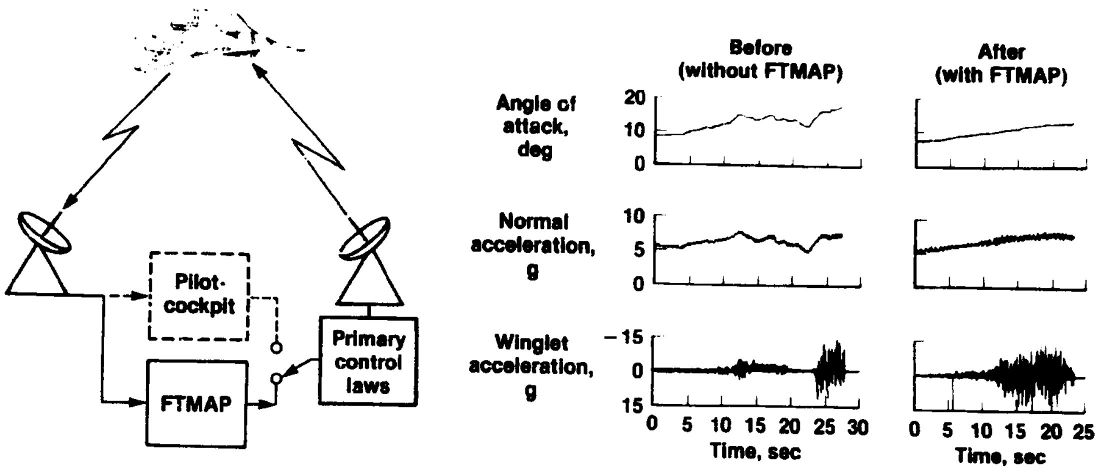


Figure 5. HiMAT flight test maneuver autopilot.

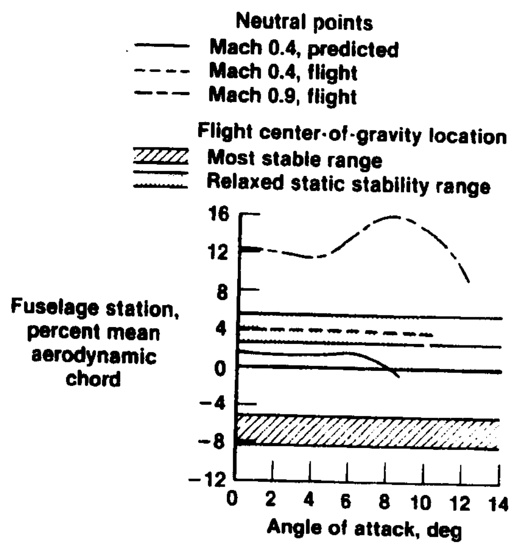


Figure 6. Neutral point and center-of-gravity ranges.

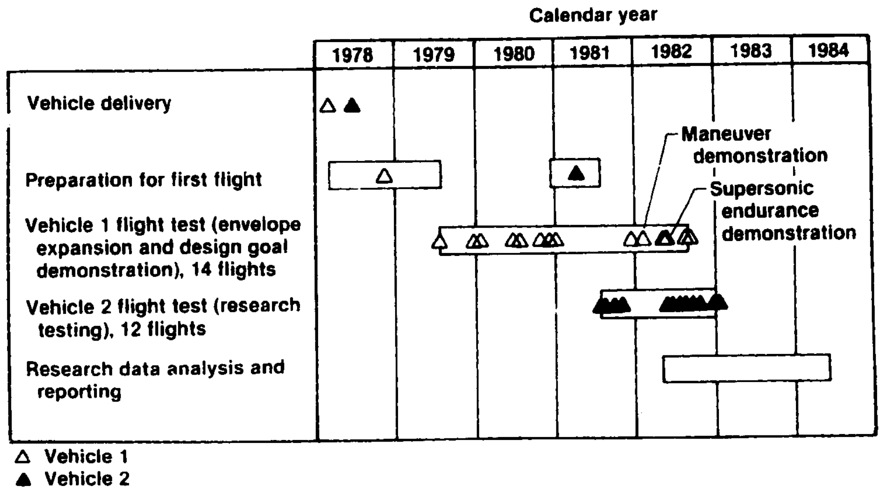


Figure 7. Flight test program schedule.

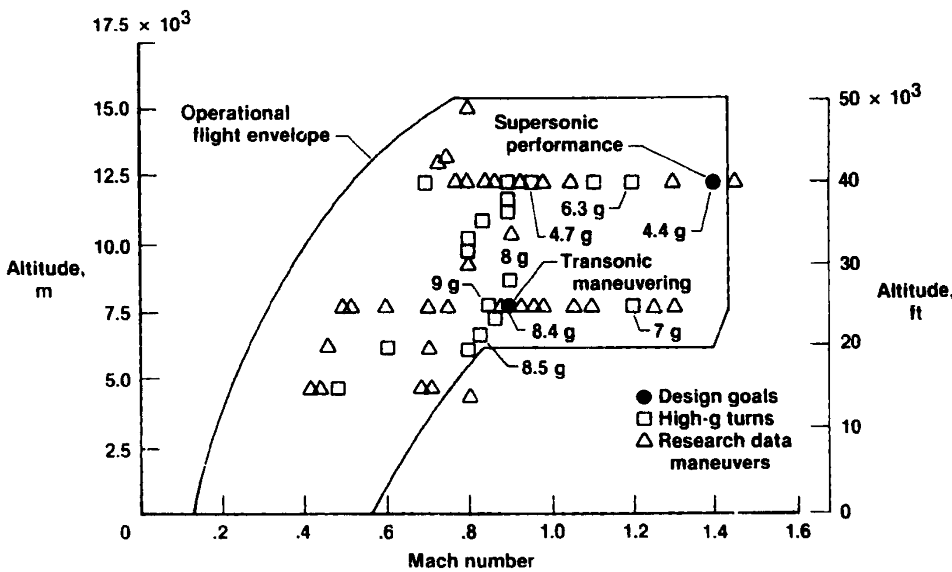
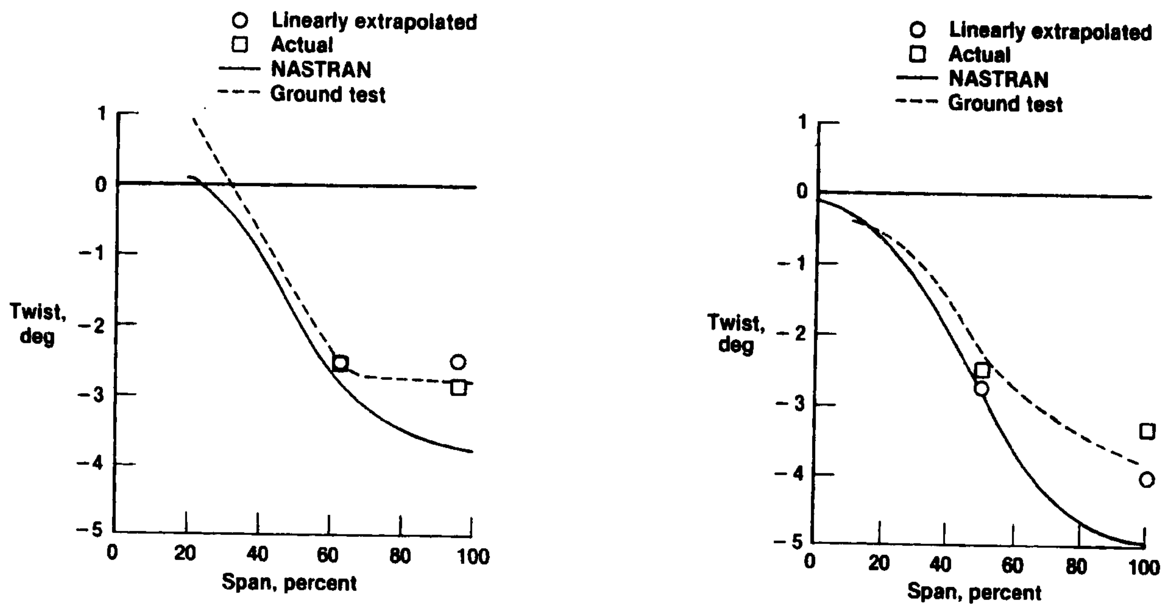


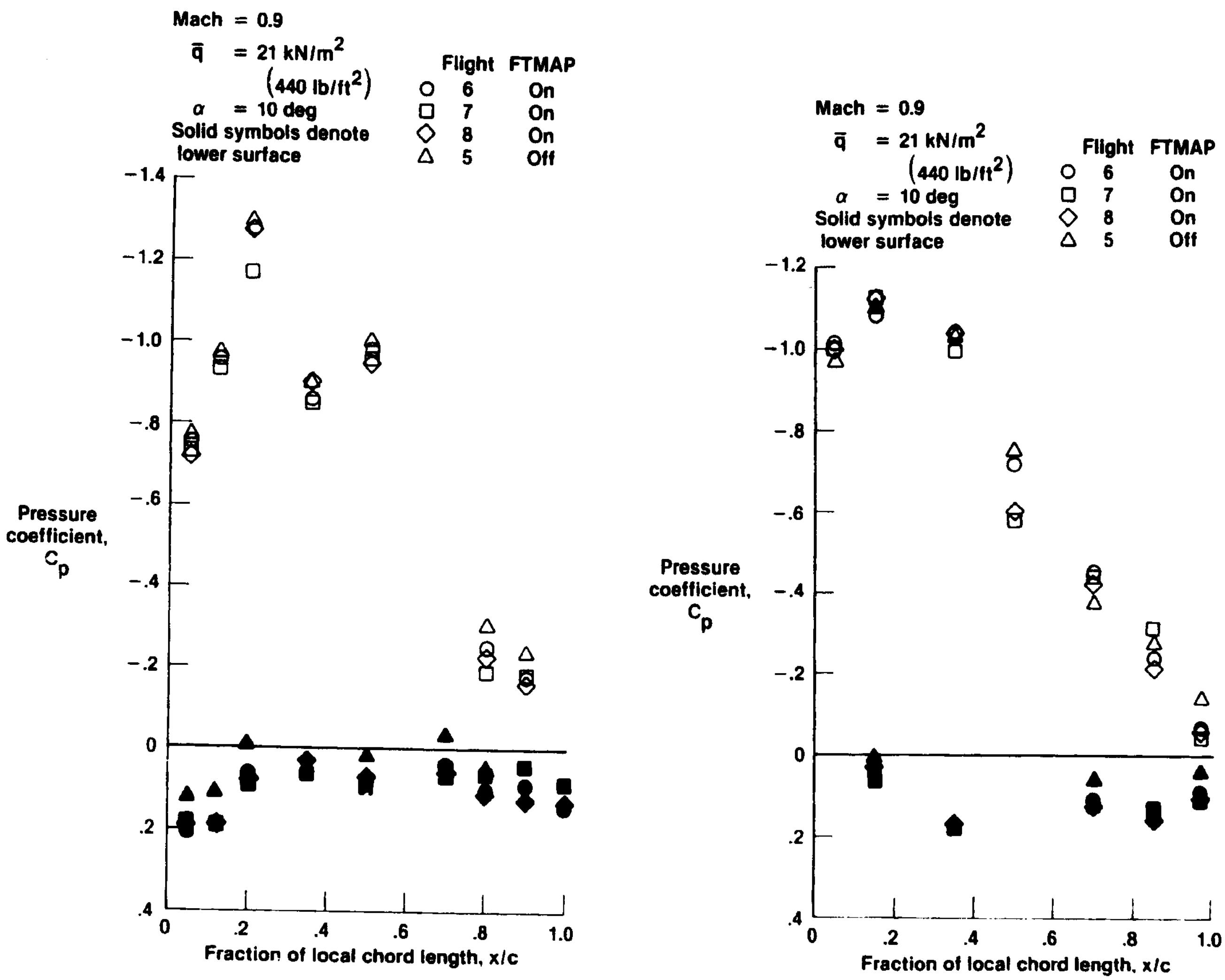
Figure 8. HiMAT flight envelope and test conditions.



(a) Canard.

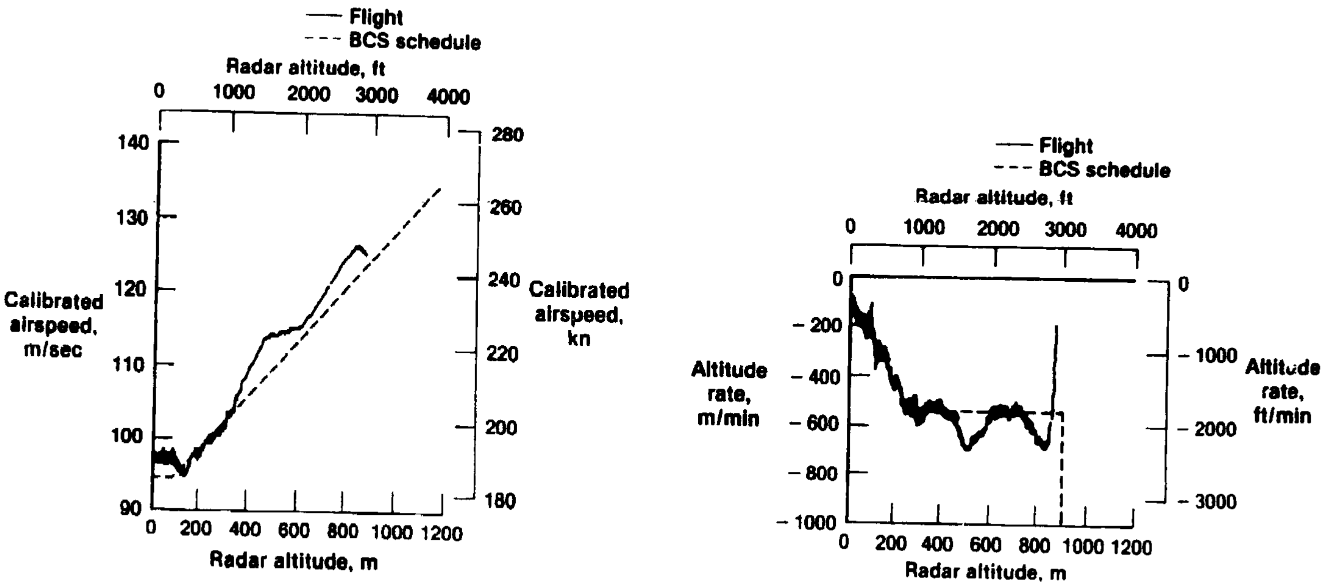
(b) Outer wing panel.

Figure 9. Streamwise twist comparisons for canard and wing panel.



(a) 0.714 wing semispan. *(b) 0.937 wing semispan.*

Figure 10. Wing pressure distribution for maneuvering flight.



(a) *Calibrated airspeed.*

(b) *Altitude rate.*

Figure 11. HiMAT landing using backup control system.

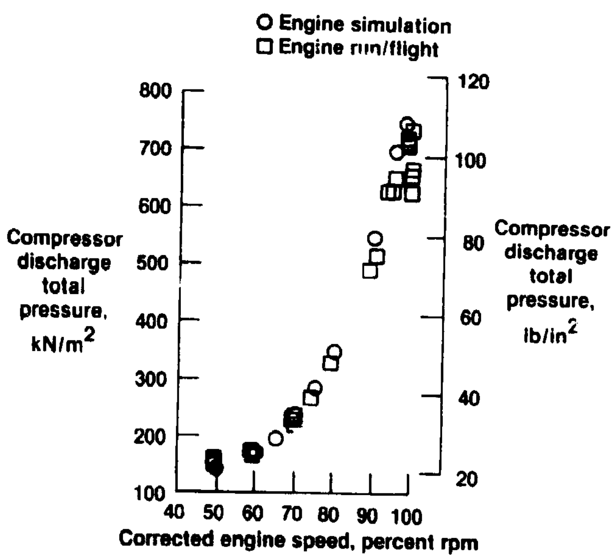
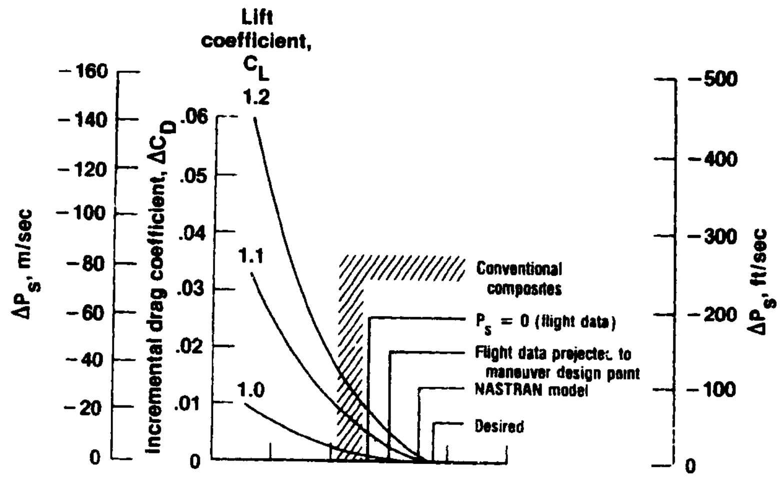
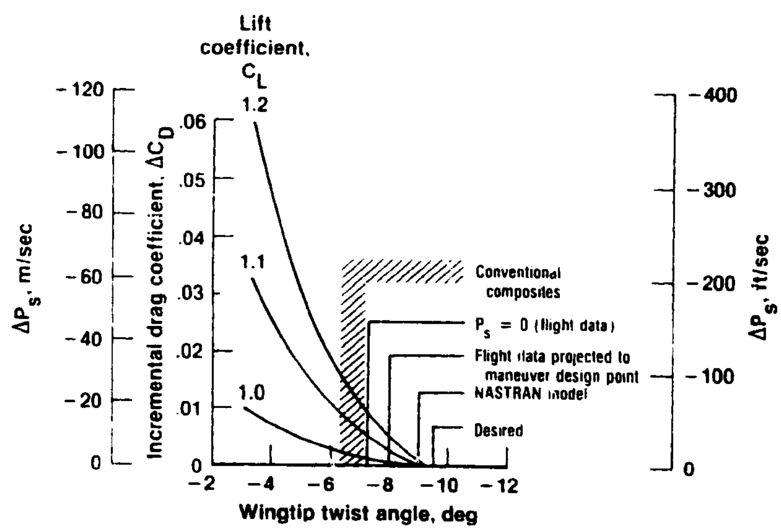


Figure 12. Digital propulsion control system performance for high-stability mode.



(a) 7620-m (25,000-ft) altitude.



(b) 9144-m (30,000-ft) altitude.

Figure 13. Effect of wingtip twist on maneuver drag at Mach 0.9.

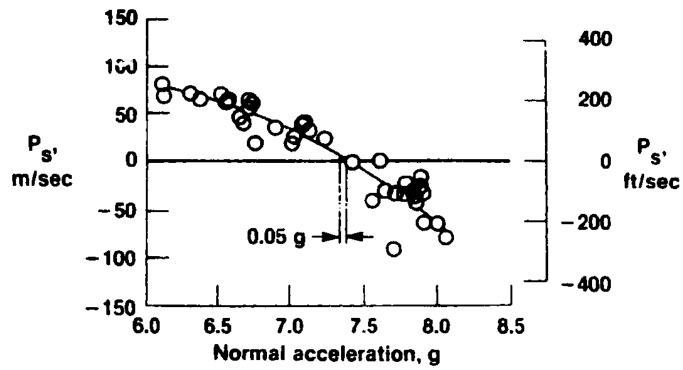


Figure 14. Flight-measured specific excess power.

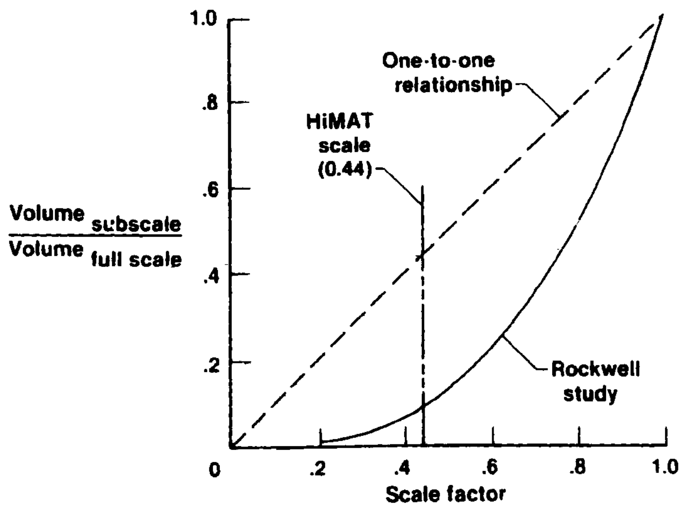


Figure 15. Vehicle volume ratio variation with scale factor.

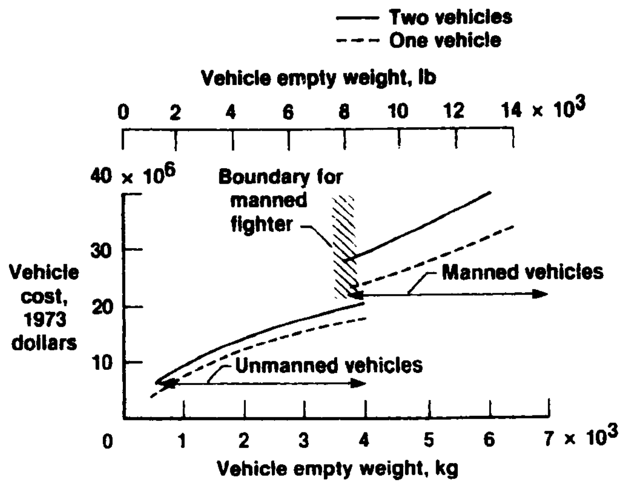


Figure 16. Comparison of estimated cost for manned and unmanned research vehicles.

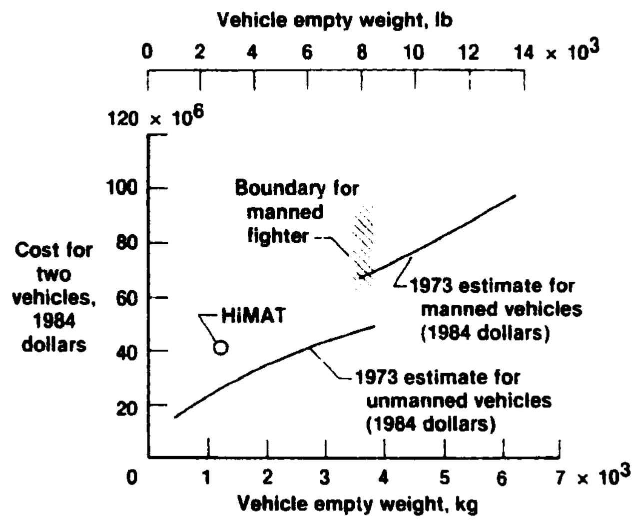


Figure 17. Comparison of HiMAT air vehicle costs with 1973 estimates.

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16. Abstract

The Highly Manueverable Aircraft Technology (HiMAT) program consisted of design, fabrication of two subscale remotely piloted research vehicles (RPRVs), and flight test. This technical memorandum describes the vehicles and test approach. An overview of the flight test results and comparisons with the design predictions are presented. These comparisons are made on a single-discipline basis, so that aerodynamics, structures, flight controls, and propulsion controls are examined one by one. The interactions between the disciplines are then examined, with the conclusions that the integration of the various technologies contributed to total vehicle performance gains. An assessment is made of the subscale RPRV approach from the standpoint of research data quality and quantity, unmanned effects as compared with manned vehicles, complexity, and cost. It is concluded that the RPRV technique, as adopted in this program, resulted in a more complex and costly vehicle than expected but is reasonable when compared with alternate ways of obtaining comparable results.

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